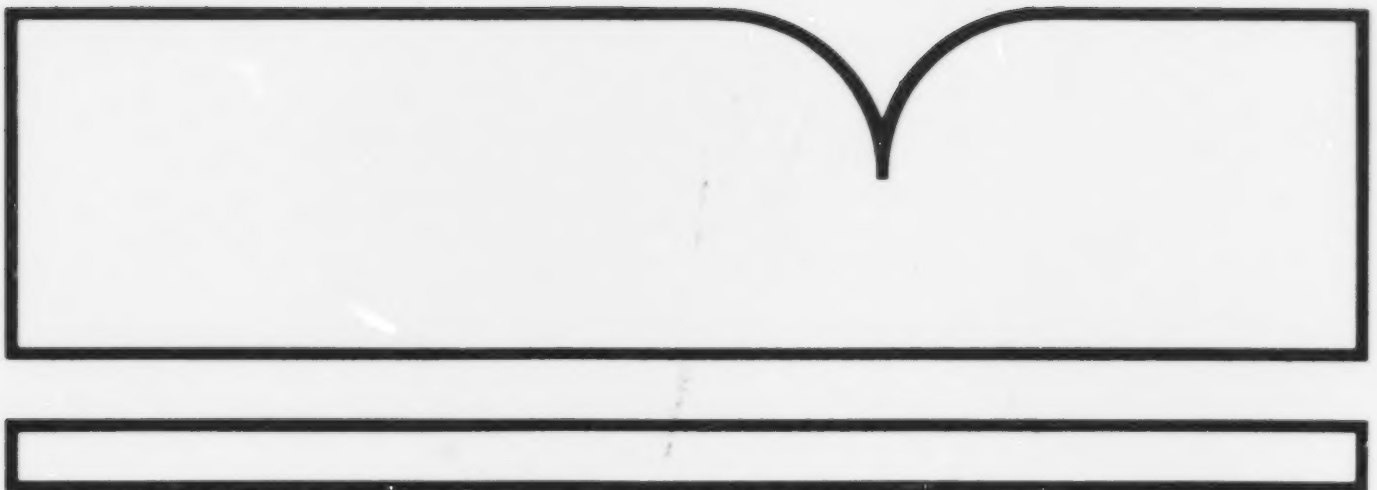


The Role of Filtration in
Preventing Waterborne Disease

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16. ABSTRACT Filtration is an important treatment process in the removal of pathogenic microorganisms and the prevention of waterborne disease. Historically, filtration was responsible for reducing death and illness from waterborne disease in 1871 in Germany. Other early examples in the U. S. are given which demonstrate the influence of filtration on the decline of morbidity and mortality from typhoid fever. Recent waterborne disease outbreaks are examined and the causes attributed to the lack of filtration or faulty operation and maintenance of the process. Pilot plant data and results from full-scale operation are presented to illustrate the effectiveness of various forms of filtration in reducing microbial populations to concentrations that are easily controlled by disinfection.		
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JOURNAL ARTICLE:

The role of filtration in preventing waterborne disease

Gary S. Logsdon and Edwin C. Lippy

Filtration is an important treatment process in the removal of pathogenic microorganisms and in the prevention of waterborne disease. Historical records indicate that filtration was responsible for reducing death and illness from waterborne disease in 1871 in Germany and for reducing morbidity and mortality from typhoid fever in the United States in the late 1800s-early 1900s. After studying recent outbreaks of waterborne disease, the authors attribute the causes of these outbreaks to the lack of filtration or to faulty operation and maintenance of the process. Pilot-plant data and results from full-scale operation are presented to illustrate the effectiveness of various forms of filtration in reducing microbial populations to concentrations that are easily controlled by disinfection.

The original purpose of filtration in water treatment was to remove the contaminants that affected the appearance, odor, and taste of drinking water. As early as the 1820s James Simpson had designed a slow sand filter that was used by the Chelsea Water Works Company in London to improve the aesthetic aspects of polluted and turbid water from the River Thames. Almost 50 years later, and before Robert Koch demonstrated that bacteria in drinking water were the causative agents for diseases, a German health official observed that cases of intestinal disease and death rates increased notably when filtration was interrupted at the local treatment plant and the unfiltered water was delivered to residents of Altona. As the science of bacteriology developed and the causes of typhoid fever, cholera, and other diseases were understood, major emphasis was placed on the operation of filtration plants to remove bacteria as well as to provide water that was pleasant to the senses.

Water treatment technology continued to improve with the addition of disinfection, coagulation, and sedimentation to the treatment process and with further refinement of the filtration process. Public health agencies and water utilities also recognized that water treatment should be accompanied by other measures that would protect the quality of water, such as protecting watersheds from contamination, treating upstream wastewater discharges adequately, monitoring plant operations, certifying operators, and

adopting standards. From the incorporation of these protective measures into water treatment technology, a multiple barrier concept evolved. This concept was based on the idea that in the event one barrier failed, the remaining barriers reduced the impact of the failure.

The need for and importance of filtration in the control of waterborne disease is discussed from a historical perspective in this article. Also, data from several sources are presented to demonstrate the effectiveness of filters in removing bacteria, viruses, and protozoan cysts.

Water filtration as a barrier to disease

Even with the advances made in water treatment technology, outbreaks of waterborne disease continue to occur. In fact, the occurrence of reported outbreaks is increasing, as are the cases of illness associated with those outbreaks (Figures 1 and 2). Outbreaks continue to occur because the multiple barrier concept is not being enforced, and in many cases, filtration is not provided or properly applied. Some recent examples of outbreaks demonstrate the importance of these principles and indicate that current technology is not being applied to prevent waterborne disease.

Giardiasis affects 3500 people. In 1979, 18 000 people received water from a system that used three reservoirs as sources of supply and provided chlorination as the only treatment. The system had a history of failing to meet turbidity standards, of relying on antiquated chlorina-

tion facilities (one cylinder feed), of failing to maintain a chlorine residual in the distribution system, and of using a distant laboratory for analyses of coliform samples (samples reached the laboratory 3-5 days after they were collected).

An outbreak of giardiasis occurred. Investigators who studied this outbreak found: *Giardia* cysts in stool samples of 16 percent of the population; infected beaver living in one of the reservoirs; *Giardia* cysts in sediments of the distribution reservoir; positive coliform results when a local laboratory analyzed water samples; and ineffective disinfection.

This outbreak occurred as a result of a breakdown in every protective barrier that existed. The most flagrant breakdown occurred in regulatory control. Filtration was not provided because this water system had been granted a waiver from complying with turbidity regulations. The waiver was granted contingent on the following requirements: (1) turbidity did not interfere with disinfection, (2) turbidity did not prevent maintenance of chlorine residual in the distribution system, and (3) turbidity did not interfere with coliform determinations. An aroused public demanded that filtration be provided not only to prevent further illness but also to prevent muddy tap water every time a rain storm occurred.

The wild and wooly West. In 1980 approximately 800 people in a western US community of 2000 were affected with giardiasis in a two-month period. The community used a local mountain stream as a source of supply and "touched it" with chlorine. Investigators found that a 200-mm (8-in.) main and a 250-mm (10-in.) main were used to collect water from the stream. The mains routed water through a chlorine injection facility and then transmitted water to the community. For some unknown reason, only water in the 250-mm main had been disinfected. The outbreak coincided with heavy rainfall that caused flooding and washout of

beaver lodges in the watershed. Corrective measures included renovating the chlorination facilities and developing plans for providing adequate treatment with filtration as a primary requirement.

Treatment breaks down and so do 2000 people. In 1981, 58 percent of the population in a community of 3400 people became ill with diarrhea, vomiting, and abdominal pain. Because the community's main source of supply was not capable of sustaining demands, an auxiliary source had been placed into service. Coincident with an overflow of untreated sewage from an upstream community, the chlorinator at the water plant broke down. The next day reports of illness were flooding local physicians, and the hospital emergency room was deluged with patients.

Investigators estimated the economic impact of this outbreak to be \$170 000. They stated that the cost was minimized because physicians prescribed medication by phone, thereby precluding the cost of office visits, and because the onset of illness occurred on Friday, allowing people to recover without missing work.

A breakdown had occurred in water treatment. Chlorination and standby facilities should have been ready to operate at the time of failure. Inspection of the filters revealed severe channeling and a plugged underdrain system, which resulted in effluent turbidity readings in excess of 4 ntu. The operator should have recognized that the filters were not working properly. Appropriate maintenance could have prevented the outbreak.

The previous examples from recent years show the serious effect of inadequate chlorination or filtration or both. Examples from an earlier era, before chlorination was practiced, can also be cited, shedding some light on the efficiency of water filtration as a barrier to pathogenic bacteria.

Hamburg-Altona—a costly lesson. A frequently cited example of the benefit of water filtration is the Hamburg-Altona episode, described in a modern publication¹ and detailed by Hazen in an early text.² In 1892, these German cities pumped their water from the River Elbe. Hamburg's water was settled, but Altona's water was treated by slow sand filters, the first of which had been built by an English company in 1860.² The 1892 epidemic involved nearly 17 000 cases of illness and 8600 deaths, with more than 8100 deaths occurring between August 16 and September 21. The extent of the epidemic, which provided evidence that the source of illness was drinking water, coincided with the boundary of the water distribution systems of Hamburg, Altona, and Wandsbeck. The tragic aspect of this event is that the knowledge gained from similar but much smaller outbreaks of illness in Altona 20 years earlier was ignored in Hamburg.

In the 1870s, two small outbreaks of cholera occurred after unfiltered water was temporarily provided to residents of Altona.² In 1870 a cholera outbreak proved fatal to 43 children in February, after unfiltered water had been provided for only a few days in January. In 1871, both unfiltered and filtered water were provided in Altona from August 11 to August 18. An outbreak of cholera extended to all parts of the city by August 19, and cases of illness peaked by August 26. The death toll was 105 from cholera and 186 from diarrhea. Thus, two decades before the very serious epidemic occurred in Hamburg, the danger from unfiltered water had been illustrated along with the capability of slow sand filters to remove enteric pathogenic bacteria.

Hazen translated the 1892 report of a Dr. Reincke, who quoted a Dr. Kraus. In discussing the 1871 outbreak in Altona, Kraus wrote, "The action of the authorities was then justified when they forbade in future the supply of unfiltered water except in cases of most urgent necessity, as in case of general conflagration, and in such a case or in case of interruption due to broken pipes, that the public should be suitably warned." Hazen reported that Kraus became the health officer of Hamburg and, in 1874, urged that sand filtration be adopted for water treatment in that city. The failure to follow his advice was extremely costly in terms of illness and death in 1892.

In Hazen's discussion of operating problems encountered in European treatment plants, he pointed out that ice formation can interfere with the performance of slow sand filters. Ice covered Altona's open filters during very cold winters, reducing the efficiency of the filters in removing bacteria. Mild epidemics of typhoid fever generally occurred in Altona during winter months.

Albany, N.Y. In 1923, Willcomb³ reported the results of two decades of water filtration at Albany, N.Y. In the late 1800s, Albany used the sewage-contaminated Hudson River as a water source when the city's needs exceeded the capacity of the upland sources. In 1899 a slow sand filtration plant was placed in operation to treat the Hudson River water. Chlorination with calcium hypochlorite was begun in 1909; after 1916, liquid chlorine generally was used. Figure 3 shows the typhoid fever death rate before and after filtration. The beneficial effect of filtration is quite obvious.

The inundation of the filtration plant at Albany during the 1913 Hudson River flood was a contributing factor to the high death rate that year. Horton⁴ showed that the 1913 outbreak was related to the flooding of the filter plant and the contamination of a distribution system reservoir (Figure 4). The peak of the outbreak occurred three weeks after the contamination of the plant and reservoir. This

length of time is consistent with the incubation period for typhoid fever. Horton reported that Prospect Reservoir was sterilized by using hypochlorite after the flood receded. This treatment was successful and "... accomplished an entire elimination of *B. coli* [*Escherichia coli*] type and acid colonies from the water in the reservoir."⁴

Cincinnati, Ohio. The performance of rapid sand filtration as a barrier to the passage of pathogenic bacteria into finished water can be observed by considering early data from Cincinnati, Ohio. Figure 5 shows a substantial reduction in the typhoid fever morbidity and mortality after rapid sand filtration was adopted, as well as a continuing decline in typhoid fever cases after the start of continuous chlorination.⁵

Filtration and reduction of microorganisms

Slow sand filters. The ability of slow sand filters to remove bacteria from drinking water was shown by the decline in disease and death rates for waterborne diseases such as cholera and typhoid fever. Hazen² reported that the intermittent slow sand filter at Lawrence, Mass., removed between 98.31 percent and 99.41 percent of the applied bacteria from 1894 through 1898.

Hazen described results of research at Lawrence in which the relationship between removal efficiency and sand size, sand depth, and filtration rate was studied. The results are shown in Tables 1 and 2. Hazen's work indicated that finer sand, deeper beds, and lower filtration rates were more effective for bacterial removal. Although disinfection should also be practiced to provide another barrier to the transmission of pathogens, Hazen's results indicate ways in which filters can be designed and operated to minimize the burden on the disinfection process.

Hazen participated in a study of water filtration at Pittsburgh and made a major contribution to the project report.⁶ In that pilot study, two slow sand filters, each having a surface area of about 26 m² (280 sq ft), were operated from July 1897 through August 1898. Hazen concluded that preliminary sedimentation should be used before slow sand filtration at Pittsburgh because of the turbidity of water from the Allegheny River. The work at Pittsburgh showed that reduction of plate count bacteria by sedimentation and slow sand filtration generally was about 99 percent or higher, except during December-January 1897-1898. During the cold weather, bacterial reduction ranged from 97.2 percent to 98.9 percent. The highest monthly average reduction reported was 99.96 percent in October 1897.

Morris Knowles, the resident engineer for the Pittsburgh pilot filtration, described a study of the effect of filter scraping on water quality.⁶ Effluent from

a slow sand filter was sampled at frequent intervals several times after the filters were scraped in the summer of 1898. Results in Table 3 show that for two days after scraping, bacterial counts were substantially higher than monthly arithmetic mean counts; the 48-hour postscraping data were excluded from the monthly means. Differences between monthly means and postscraping means were statistically significant at the 0.05 level for all five sets of data.

The start-up after scraping consisted of operating the filter at 0.002 mm/s (0.25 million gallons per acre per day [mgad]) for 15 min, increasing the rate to 0.005 mm/s for 15 min, and then increasing the rate by 0.005 mm/s at 15-min intervals until the desired operating rate was attained. These results suggest that even with careful start-up procedures, the bacteriological quality of filter effluent produced for one or two days after start-up may be inferior to that of the effluent produced during the rest of the run. Therefore, it may be desirable to provide facilities for wasting filtered water for a while after start-up.

Jordan presented data on the operation of slow sand filters at Indianapolis,⁷ where filtration was preceded by sedimentation that was sometimes supplemented with coagulation. For the months of March through November from 1915 through 1919, overall plant efficiency in removing bacteria without disinfection was 99.2 percent to 99.9 percent for *B. coli*. For December, January, and February, the *B. coli* reductions were 96.0 percent, 94.1 percent, and 97.2 percent, respectively. This is another example of decreased efficiency in removing bacteria during cold weather.

Jordan also reported that the slow sand filters were not enclosed when built. However, operating problems were encountered during the first winter of operation, and as a result the filters were enclosed. In cold climates, ice can form on top of slow sand filters, causing difficulties with normal operations and severe problems when terminal head loss has been attained and the filters must be scraped.

Huisman and Wood¹ reported that tests of working filters showed reduction of total bacteria by factors of 1000 to 10 000 and reduction of *E. coli* count by factors of 100 to 1000. They also reviewed modern slow sand filter design and operating practices.

The Drinking Water Research Division of the US Environmental Protection Agency (USEPA) has been operating a 0.21-m² (2.2-sq ft) slow sand filter since November 1980.⁸ In this research, clear water, which usually has a turbidity of 1 ntu, from a gravel pit has been spiked with residential sewage and filtered at about 0.033 mm/s (3 mgad). Water samples are collected and analyzed for turbid-

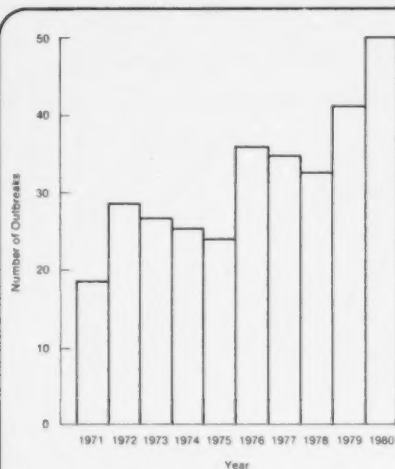


Figure 1. Reported waterborne disease outbreaks in the United States—1971–1980

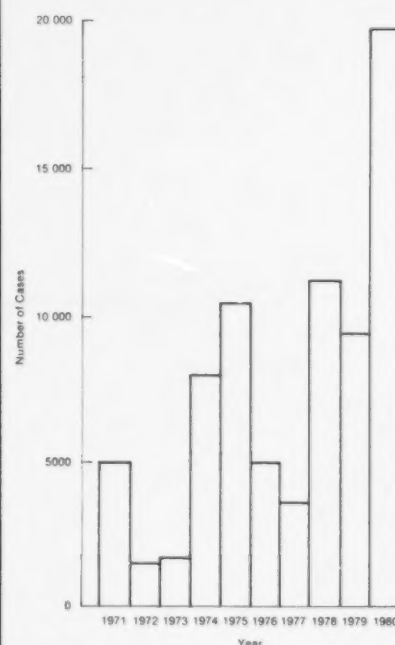


Figure 2. Reported cases of illness in waterborne disease outbreaks in the United States—1971–1980

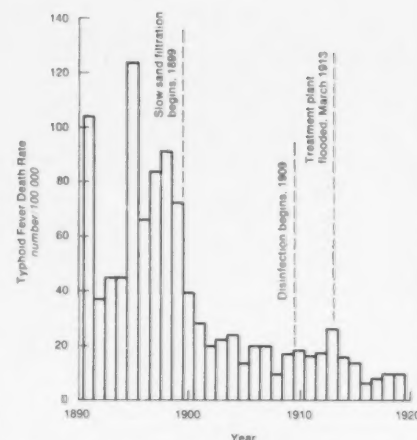


Figure 3. Reduction of typhoid fever by water treatment at Albany, N.Y.

From Willcomb,³ Table 4

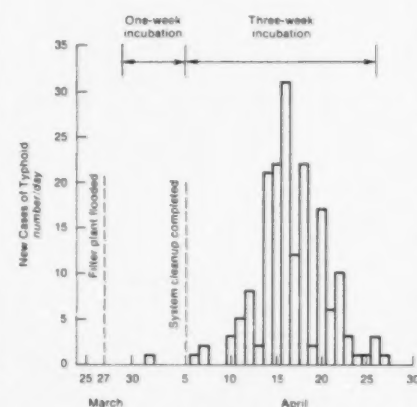


Figure 4. Typhoid fever outbreak at Albany, N.Y.—1913

From Horton⁴

ity, particle count, standard plate count, and coliforms. Results from 12 months of operation are shown in Figures 6 and 7. Coliform count was generally reduced by 99 percent or more. Coliforms were not detected in most filtered water samples even when raw water coliform counts ranged from 1000 to 10 000 per 100 mL.

Virus removal by slow sand filtration has been studied by the US Public Health Service (USPHS) and by the Metropolitan Water Board of London. The USPHS studies⁹ were performed with clean sand. At typical slow sand filter rates, virus

removal ranged from 22 to 96 percent. Removal improved as the rate of filtration was lowered. Research with attenuated poliovirus 1 was conducted with experimental slow sand filters in London.¹⁰ A filter operating at 0.055 mm/s (5 mgad) with a media depth of 0.6 m reduced the number of viruses by 99.9 percent or more. Another experiment with sterilized media showed no significant reduction in the number of viruses. Later research by the Metropolitan Water Board¹¹ showed filtration rate was important in removing viruses. Filtration at 0.055 mm/s removed

TABLE 1
Effect of grain size on passage of *B. prodigiosus* [*Serratia marcescens*] by slow sand filtration

Effective Grain Size mm	Bacteria Remaining in Filtered Water—percent	
	1892 Data	1893 Data
0.38		0.16
0.29		0.16
0.26		0.10
0.20	0.13	0.01
0.14	0.04	0.03
0.09	0.02	0.02

Source: from Hazen²

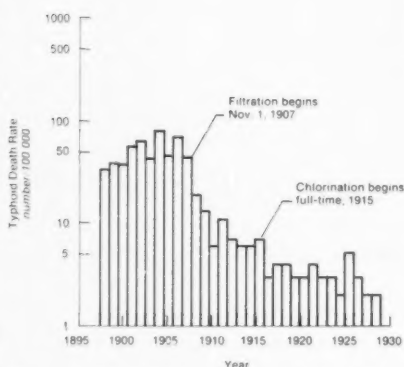
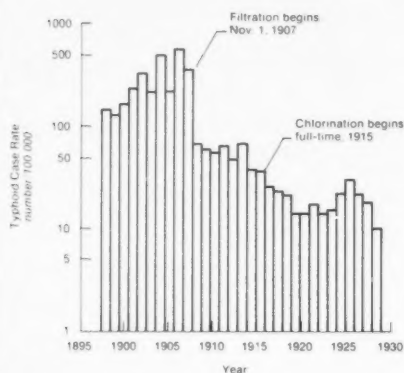


Figure 5. Typhoid fever experience at Cincinnati, Ohio—1895–1930

TABLE 2
Effect of bed depth and filtration rate on passage of *B. prodigiosus* [*Serratia marcescens*] by slow sand filter

Number of Filter	Bed Depth <i>m</i>	Effective Size of Sand <i>mm</i>	Filtration Rate <i>mm/s</i>				
			0.013	0.011	0.016	0.022	0.033
			Bacteria Remaining in Filtered Water—percent				
33A	1.52	0.14	0.002			0.040	
34A	1.52	0.09	0.001	0.005		0.020	
36A	1.52	0.20			0.050		0.050
37	1.52	0.20			0.010	0.130	
38	0.61	0.20	0.018		0.140	0.110	0.310
39	0.30	0.20	0.014	0.070		0.080	0.520
40	0.30	0.20		0.070		0.090	
42	0.30	0.20	0.016			0.150	0.550
Average			0.010	0.048	0.067	0.088	0.356

Source: from Hazen²

TABLE 3
Effect of slow sand filter scraping and restart on bacterial quality of filtered water at Pittsburgh—June–August 1898

Filter Number	Month	Filtration Rate		Sampling Period After Scraping			Monthly Average Plate Count number/mL	Average Plate Count + Monthly Average Plate Count
		mgad	mm/s	Length of Period hours	Number of Samples	Average Plate Count number/mL		
1	June	2.8	0.030	30	18	459	112	4.1
2	June	2.9	0.033	21	11	139	68	2.0
1	July	2.9	0.033	8	9	350	59	5.9
2	July	5.0	0.055	56	23	359	68	5.3
2	August	4.8	0.052	22	10	231	68	3.4

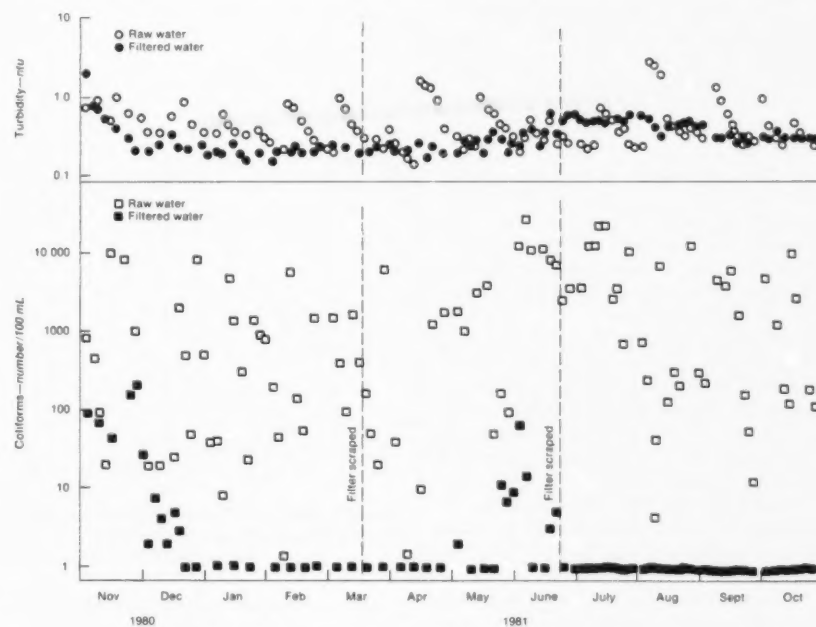


Figure 6. Turbidity and coliform data for USEPA slow sand filter

99.8 percent of the viruses, whereas filtration at 0.11 mm/s (10 mgad) removed 91 percent of the viruses. In another experiment, a reduction of 99.999 percent was obtained with filtration at 0.055 mm/s and a temperature of 11–12°C,¹¹ whereas a reduction of 99.8 percent was obtained at 6°C, again showing the effect of temperature on a filter's performance.

Information on removal of cysts by

slow sand filters does not seem to be available in the literature. Research on removing *Giardia* cysts is in progress at Colorado State University under sponsorship of the USEPA.

Rapid granular media filtration. Rapid sand filters were also studied in Pittsburgh when slow sand filters were being evaluated.⁶ An 11.0-m² (118-sq ft) Warren filter and a 10.5-m² (113-sq ft) Jewell

filter were operated at 1.3 mm/s (2 gpm/sq ft). Samples of filter effluent were collected at frequent intervals before and after backwashing to determine backwashing's effect on water quality. Some of the data from tables in the Pittsburgh report are shown in Figure 8. In each case, the number of bacteria in the effluent generally declined as the run progressed, although filter ripening occurred more

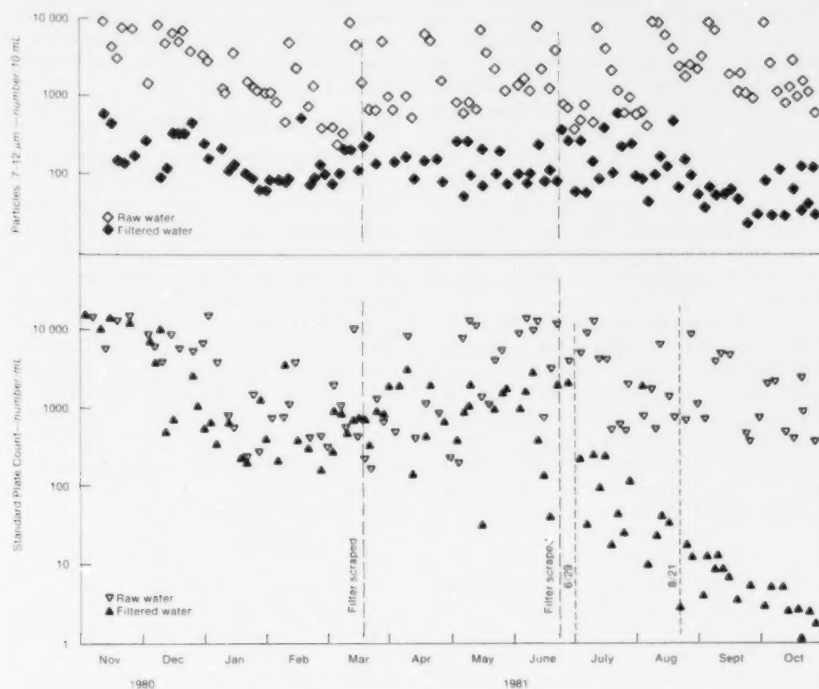


Figure 7. Particle counts and plate counts for USEPA slow sand filter

Plastic discharge tube cleaned weekly beginning 6/29; use of stainless steel discharge tube begun 8/21

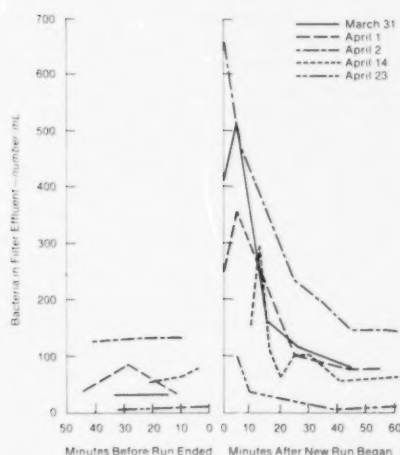


Figure 8. Effect of backwashing on bacteria in filtered water from Warren filter—1898 Pittsburgh study

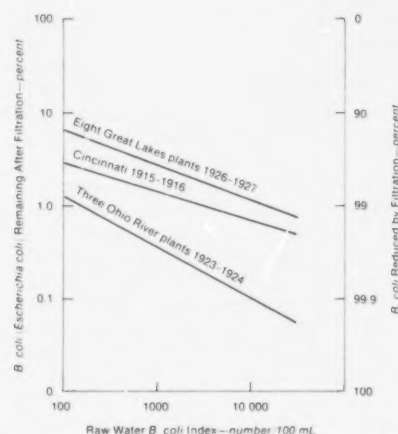


Figure 9. Effect of raw water coliform count on plant efficiency

Adapted from Streeter^{13,14}

rapidly in some runs than it did in others. Some evidence of initial degradation of effluent quality, discussed by Amirtharajah and Wetstein,¹² can be seen in Figure 8. The curves in Figure 8 resemble the typical turbidity-versus-time curves often shown by persons who discuss removal of turbidity and filter ripening. In the absence of prechlorination, both the microbiological quality and the tur-

bidity of filtered water would probably be poorer during the filter ripening period than they would be later in the run.

Treatment of uncoagulated water by rapid sand filtration at Pittsburgh was undependable and erratic for removing bacteria. Bacterial counts were reduced by 35 percent to 86 percent during operation of the Warren filter without alum for seven days in May 1898. When adequate

doses of alum were used during May, bacterial counts were reduced an average of 98.8 percent. In June, the Jewell filter was operated without alum for six days, giving reductions in bacterial counts of 38 percent to 70 percent. Removal averaged 98.5 percent in June when adequate coagulant was used.

The ability of rapid sand filters to reduce the bacterial content of drinking water was carefully studied by the USPHS during 1915-1929. Treatment of municipal sewage at that time was generally inadequate or nonexistent. Therefore, the principal barriers to transmission of waterborne disease were the die-off of pathogens in surface waters and the removal of pathogens by means of settling and filtration (and later disinfection) at water treatment plants.

According to Streeter,¹³ evaluating the capabilities of treatment plants to remove bacteria from raw waters would be necessary in order to set microbiological limits on stream and lake pollution. Figure 9 shows the percentages of *B. coli* remaining and removed as a function of the number of *B. coli* in raw water. Data from Cincinnati represent results from a plant with plain sedimentation, coagulation, sedimentation, and filtration. Filtered water samples were obtained before disinfection. In a later study, data from plants along the Ohio River—at Steubenville, Ashland, and Portsmouth—were evaluated. Ashland did not use plain sedimentation in addition to conventional treatment, whereas the other two plants did.

A group of plants along the Great Lakes was also studied, including Cleveland's Division Avenue and Baldwin plants and plants in Elyria, Sandusky, Detroit, Whiting, Evanston, and Winnetka. The well-operated treatment plants along the Ohio River were considerably more efficient in removing bacteria than plants along the Great Lakes. Streeter did not present the reasons for this difference in efficiency, but he did state that many water purification specialists considered that clear waters from the Great Lakes were more difficult to treat than turbid waters of midwestern rivers.¹⁴

More recently, Walton reviewed coliform data from numerous water treatment plants.¹⁵ He found that removals of coliforms ranged from less than 80 percent for raw water with low coliform counts to more than 99 percent for raw water with high coliform counts at three filtration plants that did not use prechlorination.

Removing viruses by means of granular media filtration has been discussed by Robeck et al.⁹ Pilot plant experiments showed that when uncoagulated water was filtered at 1.3-4.1 mm/s (2-6 gpm/sq ft), only 1 to 50 percent of the influent virus could be removed. Filtration of properly coagulated water without sedimentation removed 90 to 99 percent of the

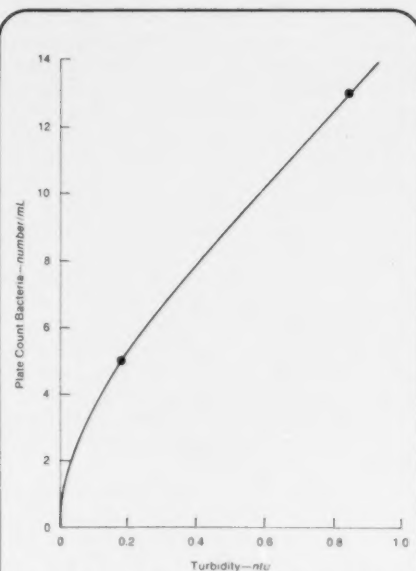


Figure 10. Relationship between turbidity and bacteria in filtered water at Vitelma plant, Bogota, Colombia—1960-63

From Hudson²¹

viruses, with removals generally exceeding 98 percent. When water had been coagulated, flocculated, and settled, filtration consistently removed 99 percent of the viruses.

The work of Robeck et al also revealed that careful control of the filtered water's turbidity was necessary for effective removal of viruses by means of filtration. When filters were producing water with a turbidity well below 1.0 ntu and passage of viruses through the filters was quite low, an increase in turbidity could signal a large increase in passage of viruses, even when the higher turbidity of the filtered water did not exceed 1.0 ntu. Effective removal of viruses depends not only on the availability of treatment facilities but also on careful operation of these facilities.

The ability of granular media filters to remove pathogenic cysts from drinking water has been a topic of interest since the 1930s. Baylis and his associates¹⁶ concluded that filtration of water through rapid sand filters at approach velocities used extensively in the United States in the 1930s (1.3 mm/s or 2 gpm/sq ft) would effectively remove cysts of *Entamoeba histolytica* from water. During World War II, research by the US Army¹⁷ showed that filtration of poorly coagulated or uncoagulated water at higher rates (4.4 and 6.6 mm/s or 6.4 and 9.5 gpm/sq ft) would not satisfactorily reduce the concentration of *E. histolytica*.

Recent USEPA research¹⁸ on dual media filtration has shown that cysts of *Giardia*

muris may pass through filters when doses of coagulant are inadequate or when raw water is not coagulated. In addition, cysts can break through during a filter run when feed of coagulant is interrupted, when the rate of filtration is abruptly increased, or when a breakthrough of turbidity occurs at the end of a filter run. However, when the USEPA's dual media filter was operated at 2.7 mm/s (4 gpm/sq ft) and the raw water was properly coagulated, reduction of these cysts generally was 99 percent or higher.

This research by the USEPA has been confirmed by filtration studies conducted with cysts of *Giardia lamblia* (obtained from human fecal specimens) by the University of Washington.¹⁹ Four filter runs that were conducted at optimum coagulant dose removed more than 99.0 percent of the cysts, whereas filter runs with uncoagulated water removed only 15 percent of the cysts.

Results of several filtration studies for removal of asbestos fibers, *Giardia* cysts, and viruses have been reviewed,⁸ and AWWA's goal of 0.1 ntu for filtered water²⁰ has been shown to be a wise choice for water utilities when removal of very small particles is a purpose of filtration. The goal of 0.1 ntu was proposed before data on removals of asbestos and *Giardia* were available. Additional support for attaining low turbidity for filtered water comes from Hudson,²¹ who used operating data from the Vitelma filtration plant at Bogota, Colombia, to show that bacterial counts in filtered water declined as the turbidity of the filtered water declined (Figure 10). McCormick and King,²² reporting on pilot-plant studies of direct filtration at five locations in Virginia, concluded, "A filtered water turbidity of 0.10 ntu, which met the AWWA goal, resulted in practically complete removal of algae and coliform bacteria."

Monitoring of the effluent from individual water filters was also proposed before recent data from filtration studies confirmed the wisdom of this practice. Continuous monitoring of turbidity at each filter is now considered to be good practice, but a precedent for this monitoring was established in Germany in the 1890s.

In a book on water filtration, Hazen² presented as Appendix I "Rules of the German Government in Regard to the Filtration of Surface-Waters Used for Public Water-Supplies." Issued in 1894, these rules included: "To allow a complete and constant control of the bacterial efficiency of filtration, the filtrate from each single filter must be examined daily. Any sudden increase in the number of bacteria should cause a suspicion of some unusual disturbance in the filter, and should make the superintendent more attentive to the possible causes of it." The same rules also stated that filters should

be designed so that they could be operated in a filter-to-waste mode when filtered water quality was inferior. This concept was once common in the United States, but it is seldom used now.

Diatomaceous earth filtration

Reducing total microscopic count. Diatomaceous earth (DE) filters can effectively remove total microscopic count (plankton and amorphous matter), but biological particles can block the filter cake and shorten the operating cycle if the dose of body feed is inadequate or the grade of diatomite being used is too fine. In a review of the performance of DE filtration plants in the state of New York, Syrotynski and Stone²³ reported the following removals: 61-92 percent of the total microscopic count and 100 percent of the plankton. The periodic use of total microscopic count is an excellent way to supplement routine data on turbidity. Particle counters, although more expensive than total microscopic count, give results much more quickly.

Removing coliforms. Hunter et al²⁴ studied removal of coliforms by means of DE filtration and concluded that penetration of the filter by coliforms was greater when the filter cake was more permeable. The most permeable grade of diatomite tested* was least effective in removing coliforms (removal was about 90 percent when the coliform count of the raw water exceeded 1000/100 mL). Another grade of diatomite† removed more than 99.0 percent of the coliforms. The finest grade of DE tested‡ removed 99.86 percent or more of the coliforms when the count of coliforms in the raw water was 19 000/100 mL and 100 percent of the coliforms when the count of coliforms in the raw water was in the range of 6 to 7000/100 mL (Table 1 of Hunter et al).²⁴

When coliforms did pass through the filter, the concentration of coliforms in filtered water increased when the number of coliforms in the influent increased. For better control of coliforms, using more permeable filter aid, which results in longer runs, should be weighed against using less permeable filter aid, which results in shorter runs but better coliform removal.

Removing viruses. Removal of viruses—T-2 bacteriophage and poliovirus Mahoney type 1—was investigated in two studies that were carried out by the University of Texas.^{25,26} The first phase of the research²⁵ showed that removal of bacteriophage was lower when a more porous grade of DE was used and higher when a finer grade of DE was used. The best removal was achieved when DE was

*Hyflo®, Manville Products Corp., Denver, Colo.

†Celite 512®, Manville Products Corp., Denver, Colo.

‡Standard Super-Cel®, Manville Products Corp., Denver, Colo.

§Mention of commercial products does not imply endorsement by the USEPA.

coated with ferric hydrate or when cationic polymer was added to the raw water. One 12-hour run was made in which cationic polymer (0.07 mg/L) was added to raw water. In 11 out of 12 samples of filtered water, no bacteriophages were detected. In one of the 12 samples, two plaque-forming units (PFU) were found. The feed water contained 1700 PFU/L. This filtration technique thus reduced the number of T-2 viruses by 99.88 percent or more.

In research with poliovirus, Malina et al.²⁶ showed that using coated DE filter aid or using cationic polymer in the raw water enhanced removal of poliovirus, compared with using uncoated diatomite. Two 12-hour filter runs were conducted to test the effects of coated and uncoated filter aid on removal of poliovirus. In one run, filter aid was coated with 1 mg of cationic polymer/g of filter aid. Twelve samples of filtered water were collected during the run. No viruses were recovered in 11 of the 12 samples, indicating >99.95-percent removal. A 99-percent removal was attained in the single sample that did contain viruses. In the other 12-hour run, uncoated filter aid and 0.14 mg of cationic polymer/L of raw water were used. No viruses were recovered from any of the 12 samples of filtered water collected during this run.

The studies just cited indicate that as particle size decreases from plankton to coliform to virus, the straining mechanism for removal of particles by DE filtration becomes less effective. However, research has shown that the use of cationic polymer can substantially enhance the removal of very small particles so that DE filtration can be a barrier to the passage of bacteria and viruses as well as to plankton.

Removing *Giardia* cysts. Research on the effectiveness of DE filtration in removing 9- μ m-diameter radioactive beads (models of *Giardia* cysts), *G. muris* cysts, and *G. lamblia* cysts has shown that DE filtration is an effective method for treating cyst-contaminated waters. Data obtained with radioactive beads indicated that a precoat thickness of 1.0 kg/m² (0.2 lb/sq ft) should be used.¹⁸ USEPA research showed that a DE filter with adequate precoat and a clean septum could consistently remove more than 99 percent of the *G. muris* cysts applied to the filter.¹⁸ Research with *G. lamblia* cysts at the University of Washington confirmed these results. Removals of cysts in four filter runs ranged from 99.03 percent to more than 99.87 percent in 12 separate determinations.¹⁹

Summary

Outbreaks of waterborne disease continue to occur and appear to be increasing in the United States. Outbreaks have not occurred where adequate treatment was provided or where plants were properly operated.

A review of old as well as recent literature shows that slow sand filters, rapid granular media filters, and DE filters are capable of removing bacteria, viruses, and cysts if designed and operated properly. Each of these filtration processes can be rendered ineffective by faulty design or by careless or improper operation.

The responsibility of the treatment plant operator is to produce safe drinking water. At slow sand filtration plants, controlling filtration rates and filtering to waste after filters are scraped are important aspects of filter operation. Effective coagulation and control of the filtered water's turbidity at rapid rate filter plants will do much to assure that filtered water has a minimum number of microorganisms. The operator can control turbidity of the filtered water more precisely by monitoring turbidity at each filter rather than at the clear well. Operators should recognize the vulnerability of filters, especially their lowered efficiency for removing bacteria, viruses, and cysts in the 30 min to 1 hour after backwashing. The grade (size) of DE selected for precoat and body feed influences removal of bacteria by DE filters. In order to remove viruses most efficiently by means of DE filtration, some modification of either the filter aid or the raw water is needed. Research has shown that raw water can be modified by using cationic polymer. DE filtration is effective for removing cysts if an adequate precoat is used and the septum is kept very clean.

References

1. HUISMAN, L. & WOOD, W.E. *Slow Sand Filtration*. World Health Organization, Geneva (1974).
2. HAZEN, A. *The Filtration of Public Water Supplies*. John Wiley & Sons, New York (3rd ed., 1913).
3. WILLCOCK, G.E. Twenty Years of Filtration Practice at Albany. *Jour. AWWA*, 10:1:97 (Jan. 1923).
4. HORTON, T. The Typhoid Outbreak at Albany, N.Y., Due to Flooded Filters. *Engineering News*, 69:20:1020 (May 15, 1913).
5. CLARK, R.M. Evaluating Costs and Benefits of Alternative Disinfectants. *Jour. AWWA*, 73:2:89 (Feb. 1981).
6. Report of the Filtration Commission of the City of Pittsburgh, Pennsylvania (Jan. 1899).
7. JORDAN, H.E. Fifteen Years Filtration Practice in Indianapolis. Proc. 13th Ann. Convention of the Indiana Sanitary and Water Supply Association (1920).
8. LOGSDON, G.S. & FOX, K.F. Getting Your Money's Worth From Filtration. *Jour. AWWA*, 74:5:249 (May 1982).
9. ROBECK, G.G.; CLARKE, N.A.; & DOSTAL, K.A. Effectiveness of Water Treatment Processes in Virus Removal. *Jour. AWWA*, 54:10:1284 (Oct. 1962).
10. TAYLOR, E.W. Forty-Fourth Report on the Results of the Bacteriological, Chemical and Biological Examination of the London Waters for the Years 1969-1970. Metro-

- politan Water Board, London, England (n.d.).
11. TAYLOR, E.W. Forty-Fifth Report on the Results of the Bacteriological, Chemical and Biological Examination of the London Waters for the Years 1971-1973. Metropolitan Water Board, London, England (n.d.).
12. AMIRTHARAJAH, A. & WETSTEIN, D.P. Initial Degradation of Effluent Quality During Filtration. *Jour. AWWA*, 72:9:518 (Sept. 1980).
13. STREETER, H.W. Studies of the Efficiency of Water Purification Processes. Public Health Bulletin 172. USPHS, Washington, D.C. (1927).
14. STREETER, H.W. Studies of the Efficiency of Water Purification Processes. Public Health Bulletin 193. USPHS, Washington, D.C. (1929).
15. WALTON, G. Effectiveness of Water Treatment Processes as Measured by Coliform Reduction. Public Health Service Publication 898. Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1961).
16. BAYLIS, J.R.; GULLANS, O.; & SPECTOR, B.K. The Efficiency of Rapid Sand Filters in Removing the Cysts of Amoebic Dysentery Organisms From Water. *Public Health Reports*, 51:46:1567 (Nov. 13, 1936).
17. Efficiency of Standard Army Purification Equipment and Diatomite Filters in Removing Cysts of *Endamoeba histolytica* From Water. War Department Report 834. Washington, D.C. (July 3, 1944).
18. LOGSDON, G.S. ET AL. Alternative Filtration Methods for Removal of *Giardia* Cysts and Cyst Models. *Jour. AWWA*, 73:2:111 (Feb. 1981).
19. DEWALLE, F.B. Removal of *Giardia lamblia* Cysts in Drinking Water Plants. Project Report for CR-806127. Univ. of Washington, Seattle, Wash., in press.
20. AWWA Statement of Policy, Quality Goals for Potable Water. *Jour. AWWA*, 60:12:1317 (Dec. 1968).
21. HUDSON, H.E. Jr. *Water Clarification Processes: Practical Design and Evaluation*. Van Nostrand Reinhold Co., New York, N.Y. (1981).
22. MCCORMICK, R.F. & KING, P.H. Factors That Affect Use of Direct Filtration in Treating Surface Waters. *Jour. AWWA*, 74:5:234 (May 1982).
23. SYROTYNSKI, S. & STONE, D. Microscreening and Diatomite Filtration. *Jour. AWWA*, 67:10:548 (Oct. 1975).
24. HUNTER, J.V.; BELL, G.R.; & HENDERSON, C.N. Coliform Organism Removals by Diatomite Filtration. *Jour. AWWA*, 58:9:1160 (Sept. 1966).
25. MALINA, J.F. JR.; BROWN, T.S.; & MOORE, B.D. T-2 Bacteriophage Removal by Diatomaceous Earth Filtration. Report prepared for the Johns-Manville Products Corp. Univ. of Texas, Austin, Texas (1971).
26. MALINA, J.F. JR.; MOORE, B.D.; & MARSHALL, J.L. Poliovirus Removal by Diatomaceous Earth Filtration. Report prepared for the Johns-Manville Products Corp. Univ. of Texas, Austin, Texas (1972).

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